NUMERICAL STUDY OF VIBRATIONS INDUCED BY TRAFFIC IN STRUCTURES AND A SCREEN ALTERNATIVE FOR ITS MITIGATION

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1. INTRODUCTION

There are numerous sources of vibrations in nature. With the progressive development of technology, sources of vibration have multiplied and have become a concern for residents of modern buildings, for sensitive equipment in, for example, hospitals as well as for those who work, visit or wish to preserve historical buildings of heritage value (Rainer 1982; Clemente et al. 1998, Gattulli et al. 2016). In particular, the vibrations induced by traffic (which has increased exponentially in recent years) have become an important environmental problem. The problems of traffic-induced vibrations on historic buildings have their origin in common characteristics in different cities of the world: the deterioration of roads, the concentration of public transport routes in adjacent streets, etc. (Crispino and D'apuzzo 2001, Kliukas et al. 2008)

In general, there are two ways in which traffic can induce vibrations in the surrounding buildings: vibrations propagated by the ground and vibrations propagated by the air (Hajek et al. 2006). The latter are low frequency sound waves that can excite the lighter non-structural components of the building. Hardly these vibrations produce architectural or structural damage to buildings (Watts 1988, 1990). The vibrations produced by traffic are usually characterized by three components: the source, the transmission medium and the receiver (Rainer 1982). The identifying and understanding of each of them simplifies the examination of its cause and the subsequent discussion of corrective measures. The source corresponds to the contact of the vehicles with the road when there are imperfections in it, impact forces and the braking force, which generates waves that propagate downwards and radially air (Hajek et al. 2006). The main variables that have an effect on the vibration amplitudes are the speed of the vehicle, its weight and type of suspension, the roughness of the running surface, and the rigidity of the wear surface and the sub-base. As for the medium of transmission, the generated waves propagate through the ground, attenuating with the distance and natural damping of the material (Mhanna et al. 2012). However, they can sometimes be channeled in a certain direction, due to soil stratifications, presenting even amplification (Rainer 1982). The receiver is the buildings in general and their occupants. Once the waves reach the foundations of the buildings, they can be amplified up to five times in their propagation to the upper floors, depending on the nature of the vibration (its frequency) and the susceptibility to vibration of the building

INTERNATIONAL JOURNAL OF ARCHITECTURAL HERITAGE
https://doi.org/10.1080/15583058.2019.1706790

elements (beams, walls, slabs, etc.) that are governed by their natural frequencies and damping (Mhanna et al. 2012).

The possibility of long-term adverse effects of vibrations in historic buildings may be of concern, especially those in a weak condition. These vibrations may not represent an imminent threat; but its repetition, its increase and its persistence over time can contribute to processes of deterioration (Clemente et al. 1998).

The effect of traffic vibrations on buildings has been studied in recent years (Hunaidi and Tremlay 1997; François et al. 2007; Pau and Vestroni 2013; Lopes et al. 2014; Vogiatzis and Kouroussis 2015). These works are especially referred to experimental determinations, whose results can be used to evaluate whether the obtained measurements are within accepted values by some regulation (Hunaidi 2000; Hanson et al. 2006), or to use values of accelerations as an excitation in a numerically modeled building (Hao et al. 2001).

It is also interesting to study the attenuation of vibrations in order to minimize their incidence through various proposed solutions, such as the use of pillars (Lu et al. 2009; Zhiefei 2013), filled ditches with stabilized floors (Korkmaz et al. 2011) and screens of attenuation (Massarsch 2004; Andersen and Augustesen 2009), use of elastic elements at the mean of conveyance (Sol-Sanchez 2015) or even proposing the building structure itself potentially as a vibration-reduction measure through parametric studies related to slabs thickness and the type of construction material, heavier or lighter structural elements, for example, wooden structures and/or long-span hollow-core concrete slabs (Persson et al. 2017). Besides those mentioned, innovative methods are being devised using novel physical concepts inspired in the periodic distribution of embedded heterogeneities in elastic media and sonic crystals concepts (Castanheira Pinto et al 2018; Godinho et al 2018; Albino et al 2019).

The installation of barriers between the source of vibration and structures is considered one of the best solutions. Among the different barriers that have proven efficacy are open ditches, full ditches (Korkmaz et al. 2011, Thompson et al 2016), sheet pile walls (Massarsch 2004; Andersen and Augustesen 2009), or even rows of columns (Lu et al. 2009; Zhiefei 2013). Due to the impedance between the different media and the topography, with the use of trenches, the amplitude of the surface vibration generated in the base is reduced through reflection, scattering and diffraction of the wave propagation. Open ditches are often used as wave barriers; however, in practice, there are limitations due to their instability. In order to maintain a trench open to a considerable depth, engineers must use sheet pile walls or diaphragms on both sides of the trench to provide adequate stability and to function as a barrier (Tsai and Chang 2009).

From the work developed by Woods (1968), the use of barriers to reduce soil vibrations has been widely studied. Several investigations were carried out on the effectiveness of these barriers, through field tests and numerical simulations using the Contour Method, the finite element method (FEM), and the combination of these. In order to study the effectiveness of trenches in the attenuation of soil vibrations, Woods (1968) carried out extensive field-scale tests. Based on the experimental results, some guidelines are presented regarding the dimensions of the trench to achieve a maximum reduction of soil vibrations. It was also concluded that, since it is difficult to extrapolate the results of field tests to real scales, numerical investigations are of great interest. Numerical studies of the effectiveness of the barriers for the reduction of vibrations of the land were carried out through the Contour Method (Beskos et al. 1986; Dasgupta et al. 1990; Leung et al. 1991; Al-Hussaini and Ahmad 1991; Klein et al. 1997; Kattis et al. 1999; Tsai et al. 2008). Other researchers used FEM (Yang and Hung 1997; Shrivastava and Kameswara 2002; Hung et al. 2004; Wang et al. 2009 Alzawi and El Naggar 2011; Persson et al. 2016).

Some general conclusions from numerical investigations are that trenches provide vibration attenuation more effectively than soil barriers. The depth of the trench is the parameter that has the greatest effect on the efficiency while the influence of the width could be negligible; also the source distance to the vibration is an important factor. Other conclusions are that the effectiveness of the barriers depends on the material parameters of the filling (Colaço et al. 2017).

It is important to note that models that use numerical tools to predict the behavior of structures in the face of dynamic actions caused by vehicular traffic are scarce (Lopes et al. 2016, Sadeghi and Esmaeili 2017) or, depending on the type of structures (especially masonry), practically non-existent. The same can be concluded in reference to the numerical models that allow the establishment of mitigation systems, which in general, only consider the influence of the dynamic action in the surrounding soil but do not directly take into account the action in the constructions (Lopes et al. 2014).

As stated, from the models developed for masonry and the macro-elements formulated previously for composite materials by the authors (Lopez et al 1999; Car et al. 2002; Oller et al. 2003; Quinteros et al. 2012a and 2012b; Nallim et al. 2005; Oller et al. 2005; Nallim and Oller 2008; Kohan et al. 2011; Rango et al 2013; Petracca et al. 2016) it is possible to work with a global model of finite elements that allows the treatment of traffic-induced vibrations in historic buildings and to analyze vibration attenuation alternatives, according to the location and, if applicable, to the corresponding regulations. Thus, this paper uses a general FEM formulation that allows the studying of the influence of vibrations caused by traffic on historic buildings and to propose mitigation solutions. In order to achieve this, the starting point is the realization of a geometric and mechanical survey of the structure under evaluation, as well as the surrounding constructions (Quinteros et al. 2016). With these data, the dynamic action coming from the traffic has been defined taking into account the particularities that this originates, through impulses that define the load states that are applied to the FEM code. The main structure is also modeled, as well as the land and surrounding buildings. In this way, it is possible to obtain indicative results of the model including its boundary conditions. Finally, different alternatives of vibration mitigation are analyzed with a double objective. The first one is to validate the use of the numerical tool based on an explicit finite element code, as well as the global methodology proposed. The second objective is to propose options for the mitigation using different variants of attenuation of vibrations, including parametric studies considering variations in the geometrical and mechanical characteristics of the attenuation devices.

2. STRUCTURAL ANALYSIS METHODOLOGY

https://doi.org/10.1080/15583058.2019.1706790

For this study the bell tower of the Basilica Minor and Convent of San Francisco in the city of Salta (Argentina) has been chosen which, due to its importance, integrates the most important historical corridor of the city and it was declared a National Historic Monument in 1941. The bell tower, made of four superimposed bodies that lighten upwards and culminate in a topping, has an approximate height of 52 m and is considered one of the highest in Latin America as an isolated body (Figure 1). The masonry of the tower, like that of the buildings of the time is constituted by an important content of irregular blocks of sandstone, ceramic bricks and lime mortar. The mortar has very low resistance, less than 3MPa. The foundation level is 3 meters deep (Toledo et al, 2011).

The analysis is performed with a numerical model based on Newmark "in-house" finite element code (PLCd 1991; Oñate 2009 Vol 1 & 2; Oller 2014; Escudero et al. 2016, 2017 and 2018) coupled with a spectral analysis code of the temporal response (see Figure 2). Some of these results are compared with experimental measurements of environmental vibration (Kohan and Gea 2011; Quinteros et al. 2016). The mentioned results are temporary and frequency (spectral) dynamic responses, in displacements and accelerations, in different levels of the building and different points of the surrounding environment. Likewise, both experimental and numerical results have been processed to obtain the values in spectral acceleration/displacement and decibel noise form. The numerical modeling carried out involves a study of development and research on the numerical evaluation of the transmission of vibrations from one source to various points located in the building selected for the analysis. To do this, a numerical simulation was carried out based on a three-dimensional finite element model that includes the building and the surrounding environment (land and other buildings), being perfectly capable of capturing the dynamic characteristics of the whole, with its kinematics and load boundary conditions. The model has been loaded by the dynamic action generated by traffic at the intersection of the corners where it is located.

3. FINITE ELEMENT MODEL

In this section, a description is given of the characteristics of the global model of finite elements including the building under study, the ground, the asphalt belt, the surrounding buildings and the attenuation devices. In all cases, the Serial/Parallel Mixing Theory (Oller et al. 1996; Rastellini et al. 2008) has been used to incorporate the different kinds of materials involved in the finite element model. Then a parametric study is done, which allows concluding about the efficiency of the method.

For the analysis, a sector corresponding to the roadways of two perpendicular streets next to the building, the surrounding land and the adjacent buildings corresponding to the Minor Basilica and San Francisco Convent are modeled by finite elements. It has also been modeled the homogenized ground in three independent layers with different thickness and values of elastic modules, the paved road, the tower, the surrounding buildings mentioned and an attenuation screen (see Figure 3). The dynamic behavior and its attenuation are analyzed by using the numerical procedure proposed and previously validated by the authors (Quinteros et al. 2016).

The extension of land considered in the model is a block of 119 meters in the direction parallel to Córdoba Street (see Figure 1.a), 129 meters in the perpendicular street

(Caseros St.) and 30 meters deep, considered as sufficient for capturing the incidence of all structural parts in the dynamical response. To these dimensions it is necessary to add 2 meters in each direction, which correspond to the material with absorbent dynamic capacity. Figure 3.a shows a general 3D view of the finite element model used.

Depending on the area to be discretized, the mesh used for the calculation is composed of two types of elements (Plate: triangular elements and Volume: hexahedral elements) (Zienkiewicz and Taylor 1991; Oller 2014). The plate elements used, without rotations, allow the assembly with the solid elements (Flores and Oñate 2007). The non-rotated plate elements are used to discretize walls and slabs of the surrounding buildings, the slabs of the tower in study and for the roadway, constitutively sublaminated and with the capacity to consider bending, shear and torsion stresses in the analysis (Martinez et al. 2010). On the other hand, the volume elements are used for the ground, also to discretize the elements located on the edge for absorbing vibrations so that, when they reach the edge of the model, were not reflected again. The base structure and walls of the tower and the attenuation screen proposed for the mitigation of vibrations were also modeled with hexahedral elements (see Figure 3.b). Figure 3.c shows the division of the ground into three layers corresponding to soils with different mechanical properties. While in Figure 3.d the detail corresponding to the proposed dimensions of the attenuation screen is shown. The technology of elements used allows a detailed representation of all the substructures that become part of the global model (homogenized ground, building with masonry walls, roadway, foundations, attenuation screen, etc.).

The discretization of the total domain has been made with 61415 elements, of which 57501 are hexahedral and 3914 are triangular, with a total of 64408 nodes. The development of the model is carried out using the finite element program ComPack developed by CIMNE and QUANTECH (Oller 2014; COMPack 2008).

3.1. CINEMATIC CONSTRAINTS

The displacements of the nodes belonging to the outer edge of the absorbent elements in the direction perpendicular to the surface to which they belong, have been restricted by imposing boundary conditions.

3.2. MECHANICAL PROPERTIES OF THE MATERIALS

The characteristics and mechanical properties of the materials used in the finite element model are detailed in Table 1. These properties result from the application of the Homogenization Theory (Lopez et al. 1999; Oller et al. 2005; Quinteros et al. 2012b) and the properties obtained by Toledo et al. (2011).

3.3. ACTIONS PRODUCED BY TRAFFIC

In order to analyze the influence of traffic on the structure and to propose alternatives for its mitigation, load stages are defined as functions of the circulation of vehicles, which result from the impact of the wheels in the inspection cameras of the intersection of the streets, speed bumps and brake forces. The study area coincides with the route of several

https://doi.org/10.1080/15583058.2019.1706790

lines of urban buses that circulate through one of the streets of the intersection (Córdoba St). There is a traffic light in the aforementioned corner, and since the streets are one-way, it implies that the sense of the load states coincides with the direction of circulation and does not overlap. In order to define the load stages that will be applied to the presented model (see Fig 3), the irregularities considered at the intersection of the perpendicular streets are shown in the plan view of Figure 4, with a total of six irregularities, two speed bumps in each direction of circulation and two inspection chambers. To obtain the unit pulses for the application of the loads in time (Figure 5) two parameters were set in the model as: time period (15 seconds), and circulation speed (30 km/h). With regard to the intensity of the loads the values corresponding to the weights of the vehicles (approximately 11 tons for a full urban bus and 1.5 tons for a car) are proposed. The impulses are applied in the vertical direction, perpendicular to the advance direction of the vehicles to simulate impacts, and horizontal, opposite to the advance direction to simulate braking forces. This way, the actions caused by the traffic acting in the mentioned points are obtained.

3.4. SCREENS MITIGATION

As depicted in previous section, the use of an attenuation screen is proposed in the present work as a solution alternative for the mitigation of the vibrations produced by traffic, and also the numerical analysis of its influence will be shown. In order to carry out this study, an attenuation screen is located on the perimeter of the road in both directions of vehicular circulation. The simulation allows the analysis of a screen of attenuation of different materials with a wide ranging of mechanical properties, with the intention of analyzing the incidence of its use and to be able to define the most appropriate solution depending on the economy, practicality of the construction according to the place of location and on-site availability. The dimensions and location of the screen are shown in Figure 3.d and the properties of the materials used in Table 1. The thickness of the screen and, especially, the depth do not result from a trivial analysis. A thickness of at least between 50 and 60 cm is proposed, which is appropriate for its placement and handling by the operators. While for its depth, an analysis of the incidence of the vibrations in a vertical profile of ground was realized.

A comparison of the accelerograms obtained numerically in points located on the level of roadway and to 2 meters, 5.5 meters, 9 meters, 16.2 meters and 21 meters deep are shown in Figure 6. The latter results justify the choice of a screen with the chosen depth since beyond 9.0 meters depth the incidence of surface vibrations are imperceptible or negligible compared to the values closest to the ground level.

For the isolation of vibrations and noise propagated by solid structures the chosen materials for the simulations were a concrete with mechanical characteristics corresponding to a H21 quality (according to CIRSOC 201; concrete strength equal to 21

MPa) and a commercial elastomer named Sylomer SR 110 due to its characteristics and adaptability of its format (see Table 1).

4. NUMERICAL RESULTS

First the numerical model will be validated by comparing the results obtained through the numerical simulation with those obtained through experimental measurements in a previous work (Kohan and Gea 2011). Once validated, the model will include hypothetical attenuation screens. The benchmark points used are those corresponding to the experimental measurements at levels +39.34 meters (last accessible point in the tower), +33.10 meters (second bell), +23.86 meters (first bell), +17.84 meters (rest level) and +0.00 meters (Terrain level) (see Figure 1.b).

In Figure 7, as a first approach, the comparison of an accelerogram obtained numerically with that obtained in-situ is shown. The accelerogram results from the measurement point located at ground level, and corresponds to the accelerations in the z direction (see Figure 3), and shows a favorable adjustment for the 15 second period corresponding to the numerical simulation.

4.1. FREQUENCY AND DECIBEL RESPONSES

In the modeling of vibrations induced by traffic in buildings, it is essential to verify that the levels of vibration obtained do not exceed the tolerable values, in accordance with current regulations and with the established protocols and measurement procedures. For this reason, it is necessary to use a complementary tool to analyze the vibration intensities in the points under study. There are several national and international standards that offer criteria for the exposure of human beings and buildings to vibrations, such as the International Standard ISO 2631 (Part 1 and 2) and its adopted version in our country Argentina, the IRAM 4078 standard; the Institute of German Standardization DIN defines admissible vibration limits for buildings in the regulation DIN 4150; the Swiss regulation SN 640312, Royal Decree 1367/2007, among others. For this purpose, a computation program has been developed and the main concepts and techniques implemented related to the evaluation of vibration levels are described below.

The Royal Decree 1367/2007 establishes the tolerable limits measured in decibels for different buildings and defines an index of vibration that, in decibels, is given by:

$$L_{aw} = 20 \log \frac{a_w}{a_0} \tag{1}$$

where a_w $\left[m/s^2\right]$ is the maximum effective value (RMS) of the acceleration signal (along the Cartesian direction z) with frequency weighting w_m and a_0 is a reference acceleration with a value of $10^{-6} m/s^2$.

The ISO 2631 standard defines the general requirements for the measurement and analysis of mechanical vibrations and shocks, and for the evaluation of human exposure to them. It establishes procedures for measuring vibrations and for evaluating their levels. The regulations establish different methods of evaluation and their conditions of applicability. The implemented method is known as "running RMS" and consists of a numerical method for obtaining the vibration index and is the most appropriate for simulated signals. This method considers the presence of transient shocks or vibrations using the integration in small temporary windows. The magnitude of vibration is defined as the maximum transient vibration value ($MTVV$) given as the maximum value in time of $a_w(t_0)$ defined as:

$$a_w(t_0) = \sqrt{\left\{\frac{1}{\tau}\int_{t_0-\tau}^{\tau} \left[a_w(t)\right]^2 dt\right\}} \tag{2}$$

where $a_w(t_0)$ is the instantaneous acceleration with frequency weighting; τ is the integration interval to perform the average value, meaning the length of the window; t is the integration variable and t_0 is the moment of observation time or instantaneous time.

The value of the maximum transient vibration is defined as the highest magnitude of $a_w(t_0)$ read during the period of the measurement or, in this case, of those calculated:

$$MTVV = \text{máx}\left[a_w(t_0)\right] \tag{3}$$

The way in which vibrations affect people depends on their frequency content. The ISO 2631 standard establishes the function of frequency weighting for vibrations inside buildings. The data entry is the temporal history of acceleration, which is filtered through the appropriate filters and the amplitude responses of these filters are obtained in the frequency domain.

A first comparison should be made to demonstrate the efficiency of the model. Numerical and experimental results are compared at ground level and on some building level to evaluate the amplification effects of the structure. Figure 8 shows the comparison of the $MTVV$ values with frequency weighting in decibels (dB), for the frequencies between 1 and 125 Hz (nominal frequencies) obtained numerically, with those achieved in-situ at ground level (a) and at the point of highest measurement of the bell tower (b) (Quinteros et al. 2016).

With the methodology validated by comparing numerical results with experimental results, the corresponding simulations were carried out with the consideration of the attenuation screen of two materials described above (Concrete and Elastomer). The proposed position of the screen is depicted at Figure 9 and the detail of its geometry and dimension was shown in Figure 3.d) and discussed above.

Figure 10 shows the comparison of the results obtained numerically by considering the presence of two different attenuation screen with the results obtained by means of in-situ measurements. Results in Figure 10.a) correspond respectively to those for the concrete screen proposal at ground level and at the point of highest measurement of the bell tower (+39.34 meters) while those at Figure 10.b) correspond for the elastomer screen proposal

Table 2 summarizes the values of the maximum peaks, in decibels, obtained for the described cases, highlighting in each one the attenuation percentage obtained with the presence of the correspondent screen. In each case a considerable percentage of decrease is observed, standing out the effect that the concrete screen has over the screen with the commercial elastomer.

5. CONCLUDING REMARKS

In this work the development with the application and calibration of a general numerical procedure that allows evaluating the vibrations induced by traffic in structures is presented. For the numerical simulations a bell tower of a historical heritage building, of high patrimonial value, has been chosen. The developed global model of finite elements describes reasonably the structure analyzed together with its foundations, the surrounding ground and the adjacent roadways. Likewise, the simulation proposed for the dynamic action induced by the traffic in the tower, correctly describes the phenomenon. The model, the dynamic action that simulates traffic and the numerical procedure for calculating the response, show a great capacity to analyze the dynamic vibrations at all the points of the building in which it is desired, allowing a later application of the methodology proposed to model various alternatives to mitigate the effect of generated vibrations, proposing the most convenient solutions. For this purpose, and in the first instance, a mitigation methodology by placing a screen in the ground is proposed. Through an analysis of the obtained accelerograms it is concluded an appropriate depth for the screen and two solutions are proposed with two materials of different mechanical characteristics and modes of placement. It is observed from the obtained curves, that both solutions derive in the decrease of the peaks of the accelerations product of the vibrations measured in Decibels, being slightly more effective the attenuation screen with a concrete characteristic of H21 type, resulting in an appropriate solution and totally feasible to carry out for the place where it is located.

The proposed model allows achieving greater precision in the calculation of frequencies, accelerations, as well as decibel levels, etc., only with more detailed level of considerations (enclosures, openings, partitions, etc.) and a finer discretization, which would only have repercussions in a higher computational cost but also in more faithful results to the real ones.

From the analysis of the different regulations and criteria for the evaluation of the exposure of the vibrations, it can be concluded from the obtained results that the magnitude of them are below the limits of potential damage to buildings, the maximum acceleration values are considered not annoying and also does not exceed the level of 75dB established by international regulations. It is important to consider that this condition varies with time, so it is convenient to perform periodic evaluations that allow assessing the state of the building under study. That is why the contribution of the present work is considered valuable since it represents the validation of a viable and appropriate solution to carry out if necessary, allowing the analysis of the attenuation depending on the parameters involved (dimensions and materials available).

REFERENCES

Al-Hussaini TM, Ahmad S. Design of wave barriers for reduction of horizontal ground vibration. J Geotech Eng (ASCE) 117(4):616–36, 1991.

Albino C, Godinho L, Amado Mendes P, Alves Costa P, Dias da Costa D, Sores Jr. D. 3D FEM analysis of the effect of buried phononic crystal barriers on vibration mitigation. Engineering Structures, 196: 1-11. 2019.

Alzawi A, El Naggar MH. Full scale experimental study on vibration scattering using open and in-filled (GeoFoam) wave barriers. Soil Dyn Earthq Eng 31:306–17, 2011.

Andersen L. and Augustesen A.H. Mitigation of traffic-induced ground vibration by inclined wave barriers -a three-dimensional numerical analysis. ICSV16, Kraków, Poland. 2009

Beskos DE, Dasgupta G, Vardoulakis IG. Vibration isolation using open or filled trenches Part 1: 2-D homogeneous soil. Computational Mechanics 1(1):43–63, 1986.

Car E, Zalamea F, Oller S, Miquel J, Oñate E. Numerical simulation of fiber reinforced composite materials. Two procedures. International Journal of Solids and Structures. Vol.39, No.7, pp. 1967-1986. ISSN: 0020-7683. 2002

Castanheira Pinto A, Alves Costa P, Godinho L, Amado-Mendes P. On the application of continuous buried periodic inclusions on the filtering of traffic vibrations: A numerical study. Soil Dynamics and Earthquake Engineering, 113: 391-405. 2018

CIRSOC 201. Proyecto, Cálculo y Ejecución de Estructuras de Hormigón Armado y Pretensado. Argentina, 1982 (1984 Updated)

https://doi.org/10.1080/15583058.2019.1706790

Clemente P., Rinaldis D. Protection of a monumental building against traffic-induced vibrations. Soil Dynamics and Earthquake Eng. Volume 17, Issue 5, Pages 289–296. 1998

Colaço A, Alves Costa P,Amado-Mendes P, Godinho L, Calçada R. Mitigation of vibrations and re-radiated noise in buildings generated by railway traffic: a parametric study.Procedia Engineering 199 (2017) 2627–2632

COMPack. CIMNE and Quantech-ATZ. Innovative Finite Element Code for non linear analysis of composite structures. Explicit finite element. http://tts.cimne.com/compack/, 2008.

Crispino, M., y D'apuzzo, M. “Measurment and Prediction of Traffic-Induced Vibrtions in a Heritage Building”. Journal of Sound and Vibration, 246(2), 319-335. 2001

Dasgupta G, Beskos DE, Vardoulakis IG. Vibration isolation using open or filled trenches Part 2: 3-D homogeneous soil. Computational Mechanics 6 (2): 129–142, 1990.

DIN 4150. Vibrations in buildings - Part 1: Prediction of vibration parameters. Part 2: Effects on persons in buildings. Part 3: Effects on structures. Germany, 1999

Escudero C, Oller S, Martinez X, Barbat A. A laminated structural finite element for the behavior of large non-linear reinforced concrete structures. Finite Elements in Analysis and Design. Vol. 119, 15, pp 78–94. ISSN: 0168-874X. DOI:10.1016/j.finel.2016.06.001. 2016

Escudero C, Oller S, Martinez X, Barbat A. Procedure based on composite fem technology for the resolution of concrete framed structures with masonry in-fills - comparison with Mexican building code. ASCE. J. Eng. Mech., 143(9): 04017080 /2017. ISSN (print): 0733-9399, ISSN (online): 1943-7889. DOI: 10.1061/(ASCE)EM.1943-7889.0001275. 2017

Escudero C, Oller S, Martinez X, Barbat A, Davalos C. Damage Assessment on the Modeling of a Large Scale Masonry Building. ASCE Journal of Engineering Mechanics, 144(12):04018107. ISSN (print): 0733-9399, ISSN (online): 1943-7889. DOI: 10.1061/(ASCE)EM.1943-7889.0001526. 2018

Flores FG & Oñate E. A rotation-free shell triangle for the analysis of kinked and branching shells. International Journal for Numerical Methods in Engineering 69 (7), 1521-1551, 2007.

François S, Pyl L, Masoumi H, Degrande G.The influence of dynamic soil–structure interaction on traffic induced vibrations in buildings.Soil Dyn.& Earthquake Eng.27:655–674. 2007

Gattulli V, Lepidi M, Potenza F. Dynamic testing and health monitoring of historic and modern civil structures in Italy- Structural Monitoring and Maintenance 3(1), pp. 71-90- 2016.

Godinho L, Amado Mendes P, Alves Costa P, Albino C. MFS analysis of the vibration filtering effect of periodic structures in elastic media. International Journal of Computational Methods and Experimental Measurements, 6(6): 1108-1119. 2018

Hajek J, Blaney C, y Hein D. Mitigation of Highway Traffic-Induced Vibration. 2006 Annual Conference of the Transsportation Association of Canada, Pr. Eduard Island. 2006

Hanson, C., Towers, D. A., y Meister, L. D. “Transit Noise And Vibration Impact Assessment”. FTA-VA-90-1003-06, Federal Transit Administration, U.S. Department of Transportantion. 2006

Hao, H., Ang, T. C., y Shen, J. “Building Vibration to Traffic-Induced Ground Motion”. Building and Enviroment, 36, 321-336. 2001

Hunaidi, O., y Tremlay, M. “Traffic-Induced Building Vibrations in Montréal”. Canadian Journal of Civil Engineering, 24(5), 736-753. 1997

Hunaidi O. Traffic Vibrations in Buildings. Construction Technology Updates - IRC, 39. 2000

Hung HH, Yang YB & Chang DW. Wave Barriers for Reduction of Train-Induced Vibrations in Soils. Journal of Geotechnical and Geoenvironmental Engineering 130(12), 2004.

ISO 2631-1. Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 1: General requirements, 1997

ISO 2631-2.Mechanical vibration and shock -- Evaluation of human exposure to whole-body vibration -- Part 2: Vibration in buildings (1 Hz to 80 Hz), 2003

Kattis SE, Polyzos D, Beskos DE. Modelling of pile wave barriers by effective trenches and their screening effectiveness. Soil Dyn Earthq Eng 18 (1):1–10, 1999.

Klein R, Antes H, Le Houédec D. Efficient 3D modelling of vibration isolation by open trenches. Comput Struct 64(1–4):809–17, 1997.

Kliukas, R., Jaras, A., y Kacianuaskas, R. “Investigation of Traffic-Induced Vibration in Vilnius Arch-Cathedral Belfry”. Transport, 23(4), 323-329. 2008

Kohan P.H., Nallim L.G., Gea S.B. Dynamic Characterization of beam type structures: analytical, numerical and experimental applications. Applied Acoustics Journal Milton Keynes (UK), 72: 975–981, 2011a.

Kohan P. H. y Gea S. B. Efecto de las Vibraciones Producidas por el Tráfico sobre la Torre de Campanario de la Basílica San Francisco. Memorias del 9º EIPAC11. Salta, Argentina. 2011b.

https://doi.org/10.1080/15583058.2019.1706790

Korkmaz K, Ay Z, Keskin S & Ceditoglu D. Investigation of Traffic-induced Vibrations on Masonry Buildings in Turkey and Countermeasures.Journ. of Vibr. and Control 17(1)3–10. 2011

Leung KL, Vardoulakis IG, Beskos DE, Tassoulas JL. Vibration isolation by trenches in continuously nonhomogeneous soil by the BEM. Soil Dyn Earthq Eng 10(3):172–179, 1991.

Lopes, P., Alves Costa, P., Calçada, R., Silva Cardoso, A., 2014. Influence of soil stiffness on building vibrations due to railway traffic in tunnels: Numerical study. Computers and Geotechnics. Volume 61, September 2014, Pages 277-291

Lopes P, Jésus FernándezRuiz J, Alves Costa P, Medina Rodríguez L & SilvaCardoso A. Vibrations inside buildings due to subway railway traffic. Experimental validation of a comprehensive prediction model. Science of the Total Environment 568 (2016) 1333–1343

López J, Oller S, Oñate E, Lubliner J. A Homogeneous Constitutive Model for Masonry. International Journal of Numerical Methods in Engineering. Vol. 46, No.10, pp. 1651-1671. ISSN: 0029-5981. 1999

Lu J, Xu B, Wang J. A numerical model for the isolation of moving-load induced vibrations by pile rows embedded in layered porous media.Inter. Jour. of Solids and Struct. 46: 3771–3781. 2009

Martinez X, Rastellini F, Flores F, Oller S, Oñate E. Computationally optimized formulation for the simulation of Composite materials and delamination failures. Comp. Part B:Eng. 42,134–144, 2010.

Massarsch K. R. Mitigation of Traffic-induced Ground Vibrations. 11th ICSDEE and the 3rd ICEGE Proceedings. Berkeley, California, USA. 2004

Mhanna M., Sadek M, Shahrour I. Numerical modeling of traffic-induced ground vibration. Computers and Geotechnics 39: 116–123, 2012.

Nallim, L.G., Oller, S., Grossi, R.O. Statical and dynamical behaviour of thin fibre reinforced composite laminates with different shapes. Computer Methods in Applied Mechanics and Engineering 194, 1797-1822, 2005.

Nallim L.G., Oller, S. An analytical - numerical approach to simulate the dynamic behaviour of arbitrarily laminated composite plate. Composite Structures Journal 85(4): 311-325, 2008.

Norma IRAM 4078 - Parte I. Guía para la evaluación de la exposición humana a vibraciones del cuerpo entero: Especificaciones generales. Buenos Aires, Argentina. 1989

Oller S., Oñate E., Miquel J. (1996). A Mixing Anisotropic Formulation for the Composites Behaviour Simulation. Communications in Numerical Methods in Engineering. Vol. 12, pp. 471,482. 1996.

Oller S, Car E, Lubliner J. Definition of a general implicit orthotropic yield criterion. Computer Methods in Applied Mechanics and Engineering.Vol. 192, No. 7-8, pp. 895-912. ISSN: 0045-7825. 2003

Oller S, Miquel J, Zalamea F. Composite Material Behavior Using a Homogenization Double Scale Method. Journal of Engineering Mechanics - ASCE. Vol. 131, No. 1, pp. 65-79. ISSN: 0733-9399. 2005

Oller, S. Nonlinear dynamics of structures. Springer, Barcelona, Spain, 2014. ISBN 978-3-319-05193-2

Oñate E., Structural Analysis with the Finite Element Method. Linear Statics: Volume 1: Basis and Solids: Basis and Solids. Lecture Notes on Numerical Methods in Engineering and Science. Springer 2009.

Oñate E., Structural Analysis with the Finite Element Method. Linear Statics: Volume 2: Beams, Plates and Shells: Beams, Plates and Shells. Lecture Notes on Numerical Methods in Engineering and Sciences. Springer 2009

Pau A & Vestroni F. Vibration assessment and structural monitoring of the Basilica of Maxentius in Rome. Mechanical Systems and Signal Processing 41: 454–466. 2013

Persson P., Persson K., Sandberg G. Numerical study of reduction in ground vibrations by using barriers. Engineering Structures 115: 18–27, 2016.

Persson P, Andersen LV, Persson K, Bucinskas P. Effect of structural design on traffic-induced building vibrations. Procedia Engineering 199 (2017) 2711–2716

Petracca M, Pelà L, Rossi R, Oller S, Camata G, Spacone E. Regularization of first order computational homogenization for multiscale analysis of masonry structures. Computational Mechanics, 57(2), 257-276. DOI 10.1007/s00466-015-1230-6. Print ISSN: 178-7675, Online ISSN: 1432-0924. 2016

Petracca M, Pela L, Rossi R, Oller S, Camata G, Spacone E. Multiscale computational first order homogenization of thick shells for the analysis of out-of-plane loaded masonry walls. Computer Methods in Applied Mechanics and Engineering. 315, pp 273–301. ISSN: 0045-7825. DOI: http://dx.doi.org/10.1016/j.cma.2016.10.046. 2017

PLCd: Non-linear thermo-mechanic finite element code for research-oriented applications. Free access code developed at CIMNE. Available from: http://www.cimne.com/PLCd, 1991-to present.

Quinteros, R., Oller, S., Nallim, L. Modelo de Degradacion Diferenciada para Materiales Compuestos. Mecánica Computacional Vol XXXI, págs. 1591-1606. X Congreso Argentino de Mecánica Computacional (MECOM 2012), 2012a.

Quinteros, R., Oller, S., Nallim, L. Nonlinear homogenization techniques to solve masonry structures problems. Composite Structures 94: 724–730, 2012b.

Quinteros, R., Oller, S., Nallim, L. Modelo de elementos finitos para predicción de la influencia de las vibraciones inducidas por el tráfico en estructuras. V Congreso Argentino de Ingeniería Mecánica, “V CAIM 2016”. 2016.

Rainer J.H. Effect of vibrations on Historic Buildings: An Overview. The Association for Preservation Technology Bulletin Volume XIV, No. 1. p. 2 -10. 1982.

Rango R.F., Nallim L.G., Oller S. Static and dynamic analysis of thick laminated plates using enriched macroelements. Composite Structures Volume 101, Pages 94–103, 2013.

Rastellini F., Oller S., Salomón O. and Oñate E. (2008). Composite material non-linear modelling for long fibre-reinforced laminates. Continuum basis, computational aspects and validations. Computers and Structures Vol. 86, pp. 879-896.

Royal Decree 1367. Whereby Law 37/2003 Of 17 November, Noise, Develops In Relation To Acoustic Zoning, Quality Objectives And Noise Emissions. Ministry of the Environment. Spain, October 19, 2007

Sadeghi J & Esmaeili MH. Safe distance of cultural and historical buildings from subway lines. Soil Dynamics and Earthquake Engineering 96: 89-103. 2017

Shrivastava RK, Kameswara Rao NSV. Response of soil media due to impulse loads and isolation using trenches. Soil Dyn Earthq Eng 22(8):695–702, 2002.

SN 640312. Swiss Standard for Vibrational Damage to Buildings. Switzerland, 1978

Sol-Sanchez M,Moreno-Navarro F, Rubio-Gamez MC. The use of elastic elements in railway tracks: A state of the art review. Construction and Building Materials 75 (2015) 293–305

Thompson DJ, Jiang J, Toward MGR, Hussein MFM, Ntotsios E, Dijckmans A, Coulier P, Lombaert G, Degrande G. Reducing railway-induced ground-borne vibration by using open trenches and soft-filled barriers, Soil Dynamics and Earthquake Engineering, 88: 45-59. 2016

Toledo MW, Vargas I, Gea SB, Nallim LG Características dinámicas del campanario de la basílica de San Francisco (Salta). Memorias del 9° EIPAC11. Salta, Argentina, 2011.

Tsai PH, Feng ZY, Jen TL. Three-dimensional analysis of the screening effectiveness of hollow pipe barriers for foundation-induced vertical vibration. Comput Geotech 35:489–99. 2008.

Tsai P.H., Chang T.S. Effects of open trench siding on vibration-screening effectiveness using the two-dimensional boundary element method. Soil Dynamics and Earthquake Engineering 29: 865–873, 2009.

Vogiatzis K, Kouroussis G. Prediction and efficient control of vibration mitigation using floating slabs: practical application at Athens metro lines 2 and 3. Int. J. Rail Transport 3 (4): 215-232. 2015

Wang JG, Sun W, Anand S. Numerical investigation on active isolation of ground shock by soft porous layers. J Sound Vib 321:492–509, 2009.

Watts, G. R. “Traffic Induced Vibrations in Buildings”. Research Report 246, Transportation and Road Research Laboratory, Crowthorne, Berkshire. 1990

Watts, G. R. “Traffic Vibration and Building Damage”. Research Report 146, Transport and Road Research Laboratory, Department of Transport, Crowthorne, Berkshire. 1988

Woods RD. Screening of surface waves in soil. Journal of the Soil Mechanics and Foundations Division (ASCE) 94(4): 951–980, 1968.

Yang YB, Hung HH. A parametric study of wave barriers for reduction of traininduced vibrations. Int J Numer Meth Eng 40(20):3729–47, 1997.

Zhifei Shi J.H. Attenuation zones of periodic pile barriers and its application in vibration reduction for plane waves. Journal of Sound and Vibration 332: 4423–4439, 2013.

Zienkiewicz O. & Taylor LR. The finite element method, McGraw-Hill, London,England, 1991.

https://doi.org/10.1080/15583058.2019.1706790